Three Dimensional Simulation of Gerotor with Deforming Mesh by using OpenFOAM

Robert Castilla, Pedro Javier Gamez-Montero, Gustavo Raush and Esteban Codina

Universitat Politècnica de Catalunya, LABSON Department of Fluid Mechanics, Colom, 11, ES-08222 Terrassa, Spain
E-Mail: robert.castilla@upc.edu

A new-born design and construction of a mini gerotor metering pump with trochoidal-teeth is presented. The technical innovation in this new-born design is to study the fluid dynamic effects of interteeth and lateral clearances by using OpenFOAM toolbox, an open source CFD software. This work is based on two critical aspects, the deforming of the mesh following the solid gears rotation, a complex interaction between mesh and gear profile surface that has to maintain a moderate quality of the mesh, and the simulation by means of a new boundary condition of the interteeth contact, reproducing actual contact points between the rotors. The posibility of contact point simulation by means of a proper mesh motion model is also suggested.
Keywords: Gerotor pump, Computational Fluid Dynamics, Dynamic Mesh, Leakage
Target audience: Mobile Hydraulics, Design Process

1 Introduction

The technology of gerotor pumps progresses towards significant number of sectors such as life science, industrial and mechanical engineering. This remarkable growth is based on its three main advantages: simplicity, versatility and performance /1/. Moreover, recent paradigm, like environmental concerns, drive the industry towards additional applications leading to growing demand for pumps that can improve their efficiency /2/. As gerotor pump specifications become more demanding and design cycles shorter, the conceptual stage becomes the most valuable guide to a cost effective design process. Here, numerical simulation with open source software appears to be the cost effective design process that leads the designer to a new gerotor pump unit with satisfactory performance and efficiency indices. More specifically, with regard to miniaturized gerotor pumps, few studies are available in the open literature with the exception of Mancò et al. /3/. The current methods of analysis of conventional components cannot be directly applied to mini components owing to geometry scale factor, kinematic and fluid dynamics. In small scales, the current knowledge, design criteria and know- how used in conventional sizes become questionable, as it is conditioned by the demanding axial and radial clearances /4/.

In this work, a new-born design and construction of a mini gerotor metering pump (mGp) with trochoidal-teeth profile intended to work at low rotational speed and low pressure is presented. Owing to manufacture tolerances and gear working performance, an interteeth radial clearance could appear tip-to-tip on mated teeth and sideway/lateral axial clearance between body pump and trochoidal-gear set. The technical innovation in this new-born design is to study the fluid dynamic effects of interteeth and lateral clearances by using OpenFOAM toolbox, an open source CFD software. As a consequence, the leakage flow in the clearances can be estimated and its important fluid dynamics effects owing to the mini size of the gerotor pump and the low working pressure and rotational speed are shown. This work is based on two critical aspects with respect to numerical methodology: (i) the deforming of the mesh following the solid gears rotation, a complex interaction between mesh and gear profile surface that has to maintain a moderate quality of the mesh by means of a dynamic-coupled mesh interface and (ii) the simulation by means of a new boundary condition of the interteeth contact, reproducing actual contact points between the rotors. For the first point, instead of using deforming and local remeshing, the use of a arbitrary coupled mesh inter- face (ACMI) approach has been adopted. An arbitrary mesh interface (AMI) allows the simulation of fluid flow across adjacent disconnected mesh domains. Nevertheless, it has the limitation that both boundaries have to be completely covered by each other. An ACMI allows the use of an AMI with partially overlapped patches. For the second point, the interteeth contact is simulated adapting the viscous wall model, although it is explored the possibility of leaving out this model if a proper motion model from mesh can be found.

2 The mini-Gerotor pump

The mini gerotor pump (mGp) is an internal gear pump with trochoidal-teeth profile. Basically, a gerotor pump consists of a pair of gears: an inner rotor with external teeth called the inner/ internal gear and an outer ring with internal teeth called the outer/external gear (see Figure 1). The two gears are mated so that each tooth of the internal gear is theoretically always in sliding contact through the line of contact with a tooth of the external gear, i.e., interteeth contact occurs; these points are known as contact points named P_k in Figure 1. Both gears are eccentric and rotate in the same direction but at different speeds, since the external gear has one tooth more than the internal gear, and consequently, the internal gear is slightly faster than the external gear.

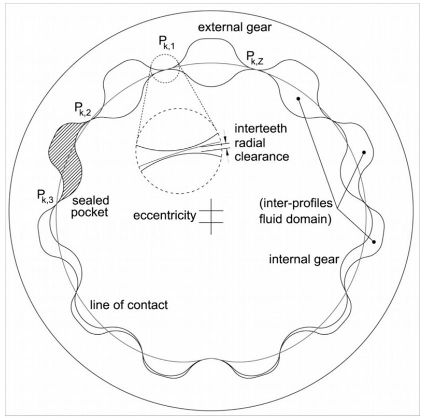

Figure 1: The internal gear with trochoidal-teeth profile, where Z is the number of external gear teeth.

In this work, a new-born design and construction of a mini gerotor pump is used. By using GEROLAB software /14/ in a first stage, the geometry, volumetric characteristics, contact stress and teeth clearance history are defined and obtained. Thus, the mini trochoidal-gear geometrical parameters are established based on analytical volumetric capacity of 0.47 cm^3 /rev. In a second stage, the theoretical porting on body and cover are established. Then, a 3 D – CAD model of the mini pump is designed as is depicted in Figure 2

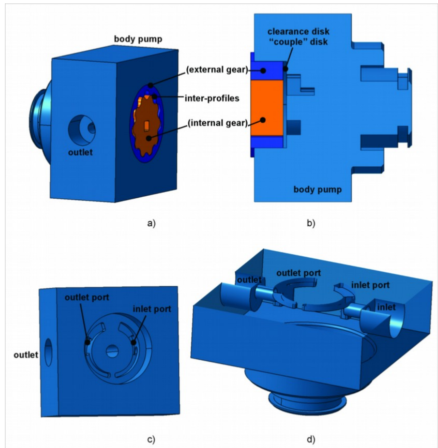

Figure 2: The mini gerotor pump: (a) 3 D - CAD model depicting the interprofiles fluid domain, (b) cross section depicting the clearance disk to model axial leakage flow named "couple" disk, (c) outlet and inlet ports, and (d) negative body section depicting the pump fluid domain without any mechanical moving parts.

3 The numerical model

The operating principle of a mini gerotor pump presents a main challenge in this numerical model: the mesh domain decomposition. The mesh domain decomposition comprises the interprofiles domain with dynamic meshing and the housing domain with static meshing. In previous works, the continuously deforming of the mesh in the interprofiles domain has forced remeshing when mesh quality decreases excessively. Then, the corresponding fields have to be mapped from one low-quality mesh to the new one. This method has been previously explored and reported with an external gear pump by the authors with 2D /5/ and 3D simulation /4,6/ with satisfactory results. Nevertheless, the leakage in the clearance disk (marked as "couple" disk in Fig. 3) at the top and bottom part of gears was not considered, and the fast mesh quality decay requires a very frequent remeshing and fields mapping. In the present work, these two issues are overcome.

3.1 The mesh

3.1.1 Meshing of pump case and clearance disk

The body pump fluid domain has been meshed from a 3D-CAD model, using snappyHexMesh. This tool provides a high-quality hexahedral-dominant mesh. Two steps are performed to generate the mesh for the gear pump fluid domain: background mesh and refine region mesh. The background mesh, generated with blockMesh, seems not to receive the attention that certainly deserves owing to its great importance to achieve a good final mesh of the fluid domain. The common used regular hexahedron element is not the most appropriate. Instead, a better mesh is obtained by using a radial configuration because of the main cylindrical geometry of the pump fluid domain. This background mesh along with the gerotor pump body geometry is shown in Fig. 3(a).

With regards to the clearance disk, in order to get more control of the number of layers, element type and cell size, the domain has been meshed directly with the blockMesh tool obtaining a layered structured mesh (see Fig. 3(b)).

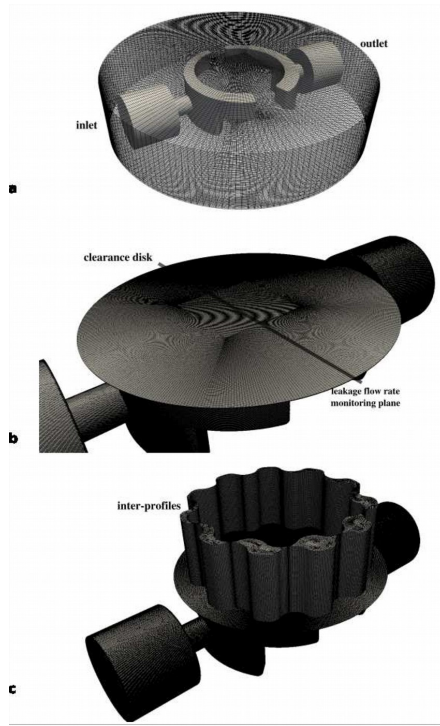

Figure 3: Mesh generation process: (a) body pump, with inlet and outlet ports and tubes, with the cylindrical background mesh used with snappyHexMesh, (b) mesh of body pump with cylindrical clearance disk mesh. The interface between the body pump and the clearance disk is an ACMI. (c) Simulation mesh with the three fluid domains: body pump, clearance disk, and interprofiles. The interface between interprofiles mesh and clearance disk is also an ACMI. The only dynamic part is the interprofiles mesh.

3.1.2 Meshing of interteeth domain

The interprofiles fluid domain meshing is an issue that requires special attention. The long term objective of the present project is to develop a methodology to support rapid simulation of any gerotor geometry. For this purpose a python code has been developed to generate the mesh without need of a CAD application. For the generation of this mesh two options have been considered.

In first place, the blockMesh program has been used for the mesh generation. The python code generates a number of points for the profiles shapes (usually around 1000) and with the help of the open source code ofblockmeshdicthelper /7/ the mesh is created. This code can handle the profiles curves as splines and generate Z blocks, one for each contact points. The mesh and the detail of the first (tip-tip) contact point are shown in Figure 4. This method has the advantage that it is fast and the mesh is structured and, hence, of high quality. On the other hand, as a drawback of being structured, it is difficult, though not impossible, to modify the number of layers in the contact point zones. As observed in Figure 4, the discretization in radial direction is the same for all the angles, and it implies large cells in some zones between contact points and small cells in the contact point zones, due to the large scale ratio.

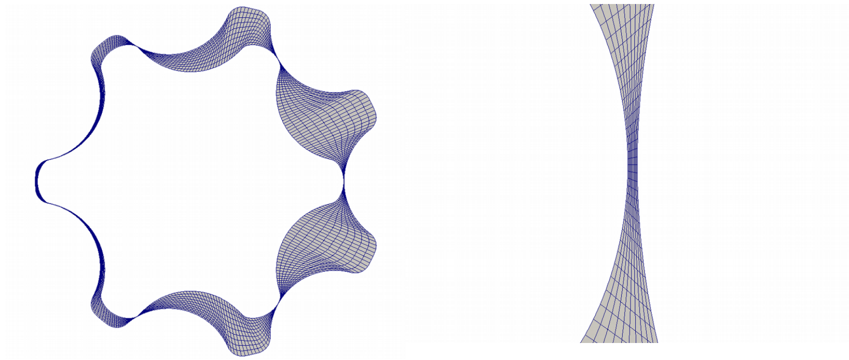

Figure 4: Mesh of interteeth domain, generated with blockMesh. Also detail of the first contact point region is shown on the right.

In order to overcome this issue, it has been explored the generation of the interteeth domain mesh with an extrusion of a 2D mesh generated with NETGEN /8/. Again, in order to automatize the process, a python code has been created using the module of Salome /9/. The generated mesh is displayed in Figure 5. The cell sizes are now more uniform, but the mesh is unstructured and the quality is not so high.

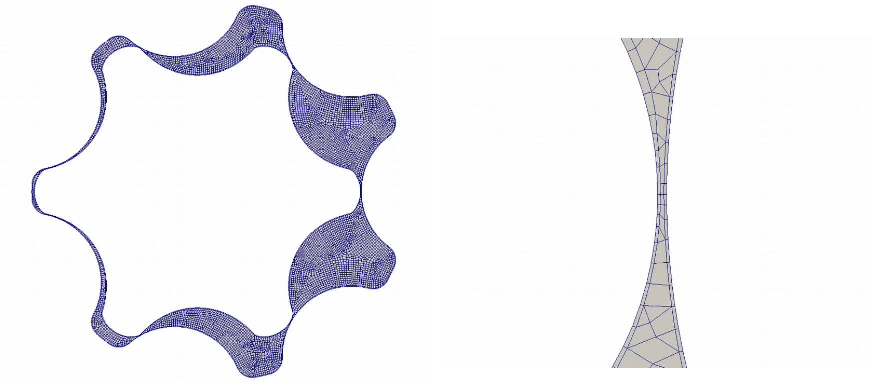

Figure 5: Mesh of interteeth domain, generated with NetGen and Salome. Also detail of the first contact point region is shown on the right.

In gap regions of the domain, where it will be contact between gears, the number of cell layers is less than in the case of blockMesh generated mesh. Nevertheless, it is considered that this cell density is not crucial for the fluid flow calculation, since, actually, there will be no relative flow in this zones when contact point is simulated.

On the other hand, one of the challenges pursued in the present work is to maintain the mesh quality in the interprofile fluid domain with the gears motion. There are two extreme approaches to this problem. First, the mesh is moved with the geometry, and it is remeshed when the quality reaches a minimum threshold value. This is the approach used in previous numerical works /5,6/ and, as pointed earlier, has the inconvenience that it requires frequent remeshing when the relative velocity is high. Second, a slip condition could be adopted for the mesh motion. In this case, the relative position of the mesh should remind constant whiles geometry moves. This leads to an incorrect cell size grading with teeth motion. The dynamic mesh process with these two extreme approaches and its results are depicted in Figure 6 for the motion in the zone of the first contact point (tip-tip contact point).

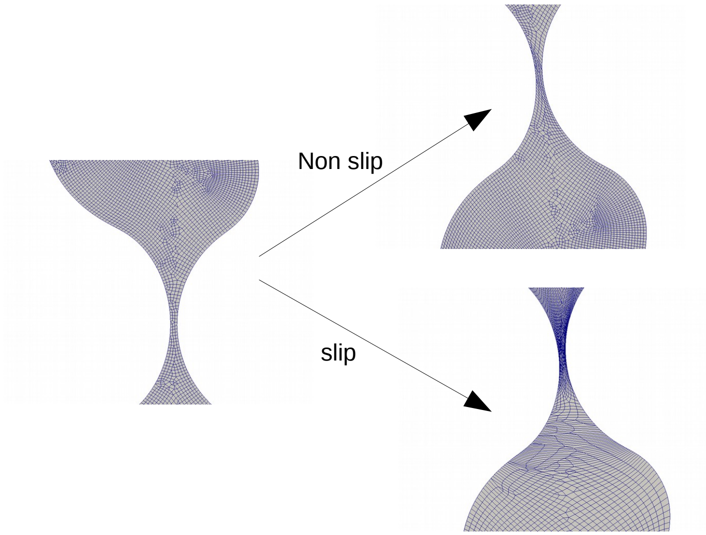

Figure 6: Dynamic mesh with the two extreme approaches of slip and non-lip condition for mesh in teeth.

It is proposed to mix both approaches with a partial slip condition. In this approach the mesh dos not move with the geometry, but with a particular angular velocity. This velocity should take a value lower than the angular velocity of the inner profile, which is the faster.

In previous works this velocity has been set has the average value between the velocity of internal profile and the velocity of the external profile. Also, the centre of rotation of the mesh has been placed in the average point between the centres of rotation of both profiles. This is a simple calculation that works properly with the contact point model proposed by this group in previous publication /1,2,6/, but has the inconvenient that the mesh does not follow the contact points positions, except for the first one (tip-tip), as shown in Figure 7

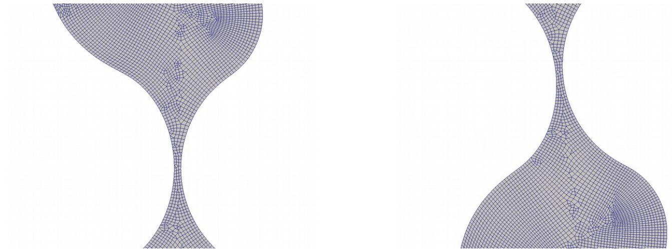

Figure 7: Dynamic mesh with the partial slip condition, with average velocity, for the first (tip-tip) contact point zone.

A more accurate calculation of the angular velocity of mesh should take into account the velocity of the contact points. This angular velocity will be then not uniform, but it will be a function of the angular position of the mesh point and of the rotational position of profiles. It is a more laborious method, but it could worth if the contact point viscosity model can then be avoided.

On the other hand, the usual way to calculate the slip velocity, by projecting the velocity difference in the plane of the geometry (see Figure 8) works fine when the number of teeth is large and concavity is low (that is, normal to geometries do not differs much of radial direction) as reported in previous works /10/ and in the results section of the present paper.

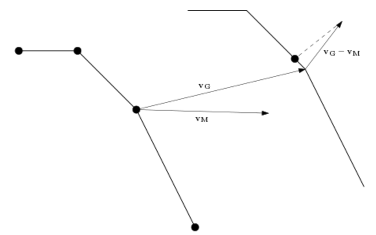

Figure 8: Point mesh calculation with slip of difference of velocities method. $\boldsymbol{v}_G$ *is the velocity of the geometry (profile) points and* $\boldsymbol{v}_M$ *is the velocity of the mesh points.*

Alternatively, when normals to geometry have a considerable tangential component, it is more accurate to calculate the point mesh position by projecting the end point of expected mesh velocity (see Figure 9).

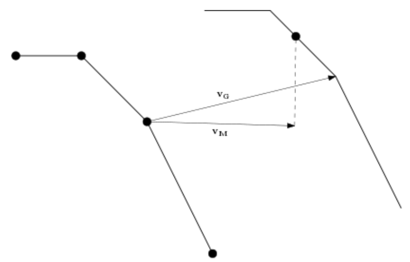

Figure 9: Point mesh calculation with projecting of mesh velocity method. $\boldsymbol{v}_G$ *is the velocity of the geometry (profile) points and* $\boldsymbol{v}_M$ *is the velocity of the mesh points.*

Finally, when mesh boundary points are moved, it is required to properly transfer this movement to the internal mesh. In this case, also two approaches can be considered. The first is to calculate the movement cells quality criteria. Unfortunately, official release of OpenFoam does not provide such functionality. Nevertheless, S. Menon /11/ developed a dynamic adaptive remeshing solver for tetrahedral meshes in OpenFoam, based on spring -analogy and the Mesquite library /12,13/. The second is to use the standard laplacian velocity based solver of OpenFoam. This group is exploring both options. The first requires a laborious process of coding and, probably, it should need a tetrahedral mesh, which would probably worsen the simulation performance. The second is giving bad quality mesh motion, but this grup thinks that it can be improved with a proper mesh velocity definition.

3.1.3 The coupling of mesh domains

The arbitrary mesh interface (AMI) is an OpenFOAM tool related to disconnected, adjacent, mesh domains being particularly useful for rotating geometries, as it is the case presented in this work. The pump fluid domain and the interprofile fluid domain require separate meshes for static and rotating regions of geometry, respectively. To couple both meshes' domains, the arbitrary couple mesh interface (ACMI) is used. The ACMI allows to couple patches that partially overlap with each other.

Special care and a precise and laborious procedure are taking to prepare the ACMI patches in the mini pump case in order to establish a methodology for the programmed dynamic simulation. Actually, in the first stage of the present project, a bug was detected in the calculation of flow mass through ACMI, but it was corrected in the version 4.0 of OpenFOAM .

Another important issue related with the ACMI is the handling of a dynamic mesh. In general, when the meshes associated to the ACMI are moving as rigid solid, it works correctly. But, when the dynamic mesh is handled by the laplacian solver, the velocity interpolation assigns an average velocity, between its corresponding velocity due to interprofiles domain mesh motion and the null mesh velocity of disk points, to the interface points, leading to an incorrect deformation of the cells in the interteeth interface zone. This generates high skew and, eventually, negative volume cells, in the mesh interface. This issue has been overcome by defining the point motion in the ACMI adjacent to interteeth domain with the velocity in an "offset" plane (typically, 1 mm above the interface) and overriding the velocity calculated by the solver. This is a considerable computation time consuming procedure, but the alternative is diving in the ACMI code in order to provide a way to separate motion zones, which are beyond the scope of the present work.

3.2 The solver

The solver, called gerotorDyMFoam, has been created as a modification of the pimpleDyMFoam, included in the OpenFoam distribution. The solver uses the finite volume method (FVM) to solve the transient Navier–Stokes equations for incompressible fluid flow. It allows the use of relatively large time steps thanks to the hybrid PIMPLE algorithm. The main modification on the solver is the inclusion of the contact point model as a transport model for viscosity, although this model could be avoided when a proper definition of the mesh velocity is properly set, as explained in section 3.1.2. Since the present work is focused mainly in the development of numerical method for ACMI and dynamic mesh, no turbulence model has been considered for the sake of simplicity, and all the simulations are laminar.

4 Results and Discussion

So far, results with large number (Z=11) of smooth teeth, with viscosity contact point model, can be presented. Simulations with projected mesh motion and high concavity teeth are still in progress, since it is not straightforward to maintain mesh quality. The reward will be to leave out the contact point viscosity model, since contact points will be constrained to mesh motion.

The simulations of a gerotor pump of theoretical volumetric capacity $Q_t = 7.83\times10^{-6}\, m^3/s$ have been conducted with a 5.25 Mcells with a clearance disk of $50\mu m$ in a HPC cluster using 64 cores. The instantenous flow rate, normalizaed with theroetical one, is displayed in Figure 10. Geometric flow rae, computed with GeroLAB /10/ is also shown for the sake of comparison.

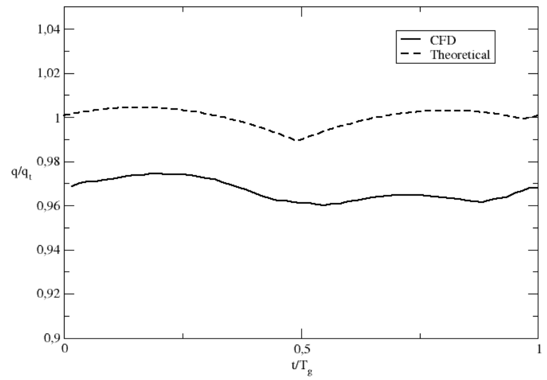

Figure 10: Instantenous flow ripple at outlet port for 1000 rpm and 1 bar of working pressure

Results plotted in Figure 10 indicates a leakage of around 3% for this clearance disk. Furthermore, a computation of flow rate in the clerance disk, displayed in Figure 11, indicates that the peak of leakage are placed in the beginning (and ending) of gearing cycle. This agrees with pressure distribution in clearance disk, shown in Figure 12. Is noticeable that higher pressure gradients, and hence, larger leakage, are placed in-between gearing cycles (subfigures a and e).

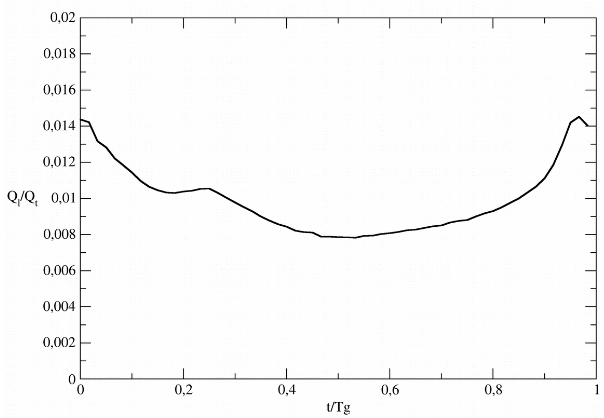

Figure 11: Instantenous flow rate in clearance disk.

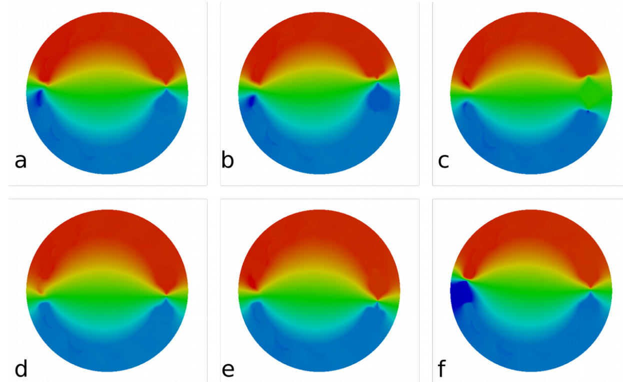

Figure 12: Pressure distribution in clearance disk.

5 Summary and Conclusion

A new method for simulation of new born mini gerotor pump is presented. This method is based on the mesh decomposition in three parts. The pump case is meshed with snappyHexMesh, and the clearance disk wih blockMesh. Two alternatives are suggested for the interteeth domain. On one hand, it can be meshed with blockMesh, obaining a structured high quality mesh. On the other hand, it an be meshed with NetGen. Also, the possibilities of surface mesh in profiles and internal mesh have been discussed. The maintenance of mesh quality is not straitghtforward when the number of teeth is low and the concavity of interprofiles chamber is high. This is a work in progress. Results have been presented for high number of teeth and low concavity, showing a leakage of 3% in the clearance disk and reveals the peak of leakage in-between gearing cycles.

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